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FINAL REPORT FOR AFOSR
GRANT NO. F49620-98-1-0030:

"MICRODISCHARGES AND RARE EARTH-DOPED WAVEGUIDE DEVICES: VISIBLE AND ULTRAVIOLET SOURCES FOR LASERS AND SENSORS"

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I. INTRODUCTION

Approximately $4\frac{1}{2}$ years ago, our laboratory embarked on a modest scale effort to explore the properties and possible device configurations of microdischarges. Only a year or so prior to our June 1997 proposal to AFOSR had we produced our first microdischarge device but in that brief period several of the attractive features of these devices had already become apparent.

The work of the past three years under AFOSR support (grant no. F49620-98-1-0030) has been more successful than we could have imagined. Most of the goals set forth in the 1997 proposal were achieved in the first year of the program and the research effort progressed rapidly on to fabricating arrays and new device concepts. A few of the accomplishments of the past three years are:

1. The demonstration of cylindrical microdischarge devices fabricated in Si and having diameters as small as 10 μm. Such devices tolerate specific power loadings beyond 100 kW-cm^{-3} and operate as hollow cathodes at pressures of 100 Torr, or more than an order of magnitude greater than those accessible to macroscopic discharges.
2. The demonstration of the continuous excitation of the rare gas-halide (and other excimer) molecules which requires the presence of a strongly attaching gas.
3. The fabrication and operation of flexible microdischarge arrays. Having a total thickness of ~30 μm, these devices are inexpensive to fabricate and amenable to mass production.
4. When screen, rather than annular, electrodes are installed on microdischarge devices, operating voltages below 100 V are routinely observed and the power consumption, radiant output and lifetime of arrays improve dramatically.
5. A new device — a microdischarge excited by a reverse-biased pn junction — has been developed.
6. Pyramidal cathode devices, entirely fabricated by VLSI processes such as RIE, have been fabricated and characterized in the Si/SiO_2 system.

As a result of this work, two patents have been issued and other applications are being prepared. Also, two small companies, ETA, Inc. in Bellevue, WA and Caviton, Inc. of Urbana,

IL and one large firm (Motorola, Phoenix, AZ) are collaborating with us in developing applications for microdischarges.

II. Accomplishments to Date Under AFOSR Grants F49620-98-1-0030 and F49620-99-1-0317

A. Microdischarge Devices Fabricated in Si or Metal/Polymer/Metal Structures

The first microdischarge devices produced in our laboratory several years ago were fabricated in Si. With cylindrical cavities varying in diameter from ~100 μm to 400 μm, these devices utilized a glass or SiO_2 dielectric ranging in thickness from 20 μm to 1 mm and a metal film (generally Ni/Cr) anode. These early devices operated at rare gas and N_2 pressures above one atmosphere, specific power loadings exceeding 10 kW-cm^{-3} and voltages of typically beyond 300 V. Furthermore, rare gas emission spectra demonstrated that 200-400 μm diameter microdischarges operate in the hollow cathode mode at pressures beyond 50 Torr, or more than an order of magnitude higher than those accessible to conventional, macroscopic discharge devices. With these devices, we were able to excite, on a continuous basis, rare gas-halide and oxide excimers such as XeI and XeO. Finally, we were able to fabricate arrays of planar cathode structures and found that, because of the resistivity of the Si substrate, the device(s) preferred to operate in a region of the I-V characteristic having a positive differential resistance and, therefore, it was not necessary to individually ballast the devices.

Since these experiments, a number of materials systems and device configurations have been explored, several of which will be described in upcoming sections. One of the most promising of these is a metal/polymer structure that has a total thickness of ~30 μm (1.2 mil) and is quite flexible. In these devices, polyimides serve as the dielectric and copper foil (25 μm thickness) acts as both the cathode and a flexible support for the device. The polymer thickness is 5-10 μm and is spin-coated onto the foil (Cu-coated Kapton film also works quite well). The anode consists of a 200 nm Ni film evaporated onto the dielectric. Operating voltages as low as 114 V are achieved, which is well below the voltages required by previous microdischarges (200-800 V) and is less than half of the sustaining and control voltages typically required for plasma display panels (PDPs). Arrays of devices are straightforward to fabricate.

Tests on scores of these devices have shown them to be robust and remarkably long lived. No evidence of deterioration of the device is evident.

Since these devices are typically only ~30 μm in thickness, and are fabricated on metal foil (or a metal-coated polymer base such as Kapton), arrays of these devices are flexible and can be manufactured quite inexpensively. For example, metal/polyimide/metal devices, can be sealed by conventional lamination and operated in 1 atm of air.

B. Screen Electrode Devices: Improved Lifetimes and Radiant Output

Replacing the annular anodes of our first generation devices with screen electrodes results in reduced power consumption, improved radiant output and lifetime of 50-150 μm diameter devices fabricated in metal/polymer structures. Single screen devices operate over a range of Ne gas pressures but, above ~400 Torr, stable operation of the "no-screen" device is restricted to a narrow current range. Of primary importance is the fact that, upon installing at least one screen electrode, operating voltages below 100 V are realized. Operating voltages as low as 90 V for a Ne pressure of 700 Torr and current of ~0.4 mA have been measured for larger (150 μm) devices. Also, the differential resistance of the screen device is roughly a factor of five smaller than that for the device without a screen electrode.

The wavelength-integrated power emitted by a 50 μm diameter device at 300 Torr Ne and I = 0.8 mA is ~14 μW, double that for a device without a screen. This output power corresponds to ~140 W-cm^{-3} of power extracted from the device. Furthermore, 50 μm diameter devices with at least one screen electrode operate as a hollow cathode at gas pressures above 300 Torr, more than a factor of three improvement over annular anode structures. Preliminary tests demonstrate that a screen electrode also significantly extends the lifetime of the microdischarge device. After operating continuously for 100 hours, for example, devices with a Ni screen anode produce > 70% of the initial (maximum) power and, when the gas is changed, return to full power. The superior characteristics of single devices having at least one screen electrode translate into improved performance of arrays. Arrays of devices without screen electrodes require considerably higher applied voltages and currents than do devices with screens.

In summary, cylindrical microdischarge devices having at least one screen electrode have been demonstrated to be superior to previous annular anode (or cathode) designs with regard to

power consumption, operating voltage, radiative output and lifetime. Operating voltages below 100 V and power loadings < 100 mW per device make these devices ideal as sources for *in situ* sensing and chemical diagnostics systems.

C. Pyramidal Cathode Devices and Arrays

Another device structure developed in our laboratory that is promising, and particularly for integrated optoelectronic sub-systems, is the pyramidal cathode device fabricated in Si. As their name implies, the heart of these devices is a square pyramid etched into Si by conventional wet chemical and photolithographic processes. This "inverted" pyramid serves as the cathode for the device. Either a polyimide film or SiO_2 serves as the dielectric and the anode is a Ni film. These devices are made in collaboration with Prof. Chang Liu of the Microelectronics Laboratory at the University of Illinois.

One attractive feature of these arrays is that ballasting of the individual devices is accomplished through the resistivity of the Si from which the cathodes are machined. Thus, the need for external ballasting of the array is generally eliminated.

It is clear that these arrays and variants that we are now pursuing, are ideally suited for integration with optoelectronic circuitry and in applications, such as medical diagnostics, where size is of paramount importance.

D. PN Junction Devices

The last microdischarge device concept that will be discussed is a novel and, we believe, exciting development. The idea is a simple one: rather than a conventional anode/ insulator/ cathode structure that, heretofore, has been used universally in microdischarges, we excite the discharge with a reverse-biased pn junction. Since the width (W) of the depletion region of a reverse-biased pn junction varies as $W \propto |V_R|^{1/2}$, where V_R is the junction bias, then it is clear that the insulator in a conventional microdischarge can be eliminated and the entire structure can be reduced to a pn junction. The implications of this concept from a fabrication standpoint are great. Furthermore, the ability to control the "insulator" (depletion region) width by varying the pn junction bias is akin to the flexibility and "remote control" offered by a varactor diode.

To demonstrate the promise of this concept, commercially-available, diodes having a reverse breakdown voltage of 400 V and manufactured by Motorola were purchased and the packing partially removed. Cylindrical microdischarge channels were subsequently machined through the pn junction by ultrasonic milling and the device voltage and current for a 280 μm diameter device are 180 V and 0.45 mA, respectively. A patent disclosure for this device concept is pending.

E. Summary

Over the past three years, we have pursued a number of microdischarge fabrication techniques and device designs and the results have been gratifying. Today, we can say that devices now operate reliably at voltages less than 100 V and pressures above one atmosphere. Furthermore, the discovery of the pn junction-excited microdischarge offers a viable approach to integrating microdischarges with electronic components *and* passive and active electro-optical components. In short, we are becoming more convinced that this technology provides an attractive pathway for integrating optical sources onto a Si electronic chip. We are grateful to AFOSR for its support of this research and believe that the results hold great promise for devices that will be ultimately of considerable value to the public.